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Multiscale Models of Melting Arctic Sea Ice

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LONG-TERM GOALS

Sea ice reflectance or albedo, a key parameter in climate modeling, is primarily determined by melt pond and ice floe configurations. Ice-albedo feedback has played a major role in the recent declines of the summer Arctic sea ice pack. However, understanding the evolution of melt ponds and sea ice albedo remains a significant challenge to improving climate models. Our research is focused on obtaining extensive imagery of melt pond evolution, and developing mathematical models of the melting process that can help us better understand the role of sea ice in the climate system, and represent sea ice more rigorously in climate models.

OBJECTIVES

Viewed from high above, the melting sea ice surface can be thought of as a two phase composite of ice and melt water. The boundaries between the two phases evolve with increasing complexity and a rapid onset of large scale connectivity, or percolation of the melt phase. We plan to document this phenomenon with photographic imagery and to develop percolation and other models to quantitatively describe the evolution.

APPROACH

Key Particpants:

Ken Golden (Professor of Mathematics, U. of Utah)
Don Perovich (Research Geophysicist, ERDC-CRREL)
Tolga Tasdizen (Associate Professor, Department of Electrical and Computer Engineering, Scientific Computing and Imaging Institute, U. of Utah)
Court Strong (Assistant Professor, Department of Atmospheric Sciences, U. of Utah)

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Chris Polashenski (Research Geophysicist, ERDC-CRREL)
Ivan Sudakov (Lorenz Postdoc in Mathematics of Climate, U. of Utah)
Bacim Alali (former Lorenz Postdoc, now Assistant Professor of Mathematics at U. of Kansas)
Ben Murphy (post-doc at U. of Utah, finished Ph.D. in 2012, now a post-doc at UC Irvine)

Alexandra Arntsen (graduate student, Thayer School of Engineering, Dartmouth College)
Meenakshi Barjatia (M.S. student in Computer Science, U. of Utah)
Kyle Steffen (Ph.D. student in mathematics)
Brady Bowen (senior in Mathematics and Physics, U. of Utah)
Boya Song (senior in Computer Science, U. of Utah)
Kasey Leavitt (freshman at U. of Utah)

Rebecca Nickerson (West High School student, Salt Lake City, currently at Yale)
Sarah Silcox (West High School student, Salt Lake City, now starting at Harvey Mudd College)
Anthony Cheng (Hillcrest High School, junior)

We describe here various facets of our approach to characterizing and modeling Arctic melt pond evolution.

Acquisition of melt pond imagery (Don Perovich, Chris Polashenski, and Alexandra Arntsen): We are developing a library of melt pond imagery that will be analyzed. This library includes aerial photographs giving complete time series of melt pond evolution during the 1997-1998 Surface Heat Budget of the Arctic Ocean field campaign plus a trans-Arctic set of photographs from August-September 2005 showing spatial variability of ponds. In addition, we are archiving satellite images from Quikbird and National Technical Means satellites.

Mapping melt pond images onto discrete networks (Tolga Tasdizen, Meenakshi Barjatia, Boya Song, Ken Golden): Given a photograph of a complex melt pond, we are developing algorithmic methods for mapping the melt pond onto a resistor network so that we can study the evolution of connectivity, look for a percolation threshold, and compute horizontal flow characteristics.

Modeling projects

We are developing mathematical characterizations of melt pond evolution using models of composite materials and statistical physics. In earlier work done just prior to this grant, we discovered that, as melt ponds grow, coalesce, and become more complex, they exhibit a transition in fractal dimension from about 1 to 2, near a critical length scale of 100 square meters. We have been pursuing a number of avenues to model the evolution of melt pond configurations and better understand the transition in complexity that real ponds display.

Continuum percolation model (Brady Bowen, Court Strong, and Ken Golden): We have developed a continuum percolation model of melt pond evolution. The sets created by the intersection of a plane (water level) with a surface generated by a random Fourier series (representing the snow and ice topography) look very similar to melt ponds, as the plane is moved up and down.

Ising model (Ivan Sudakov, Yi-Ping Ma, and Ken Golden): The Ising model has been perhaps the most widely studied model of a phase transition in statistical physics. The model describes a lattice of

magnetic spins that interact with an applied magnetic field as well as with each other. We are working to adapt this model to describe melt pond evolution. The key magnetic states, spin up and spin down, are replaced by melt water and ice.

Network model of horizontal fluid permeability (Boya Song and Ken Golden): Drainage of melt ponds can occur not only through porous sea ice below the pond, but at a distance though seal holes, cracks, etc. Horizontal flow through fluid pathways facilitates this type of drainage. We have been working on creating resistor network models of horizontal fluid flow, and computing the horizontal permeability of melt pond configurations.

Spectral measures for melt pond configurations (Ben Murphy and Ken Golden): The analytic continuation method provides rigorous integral representations for the effective transport coefficients of composite media. The key mathematical object in an integral representation is a so-called "spectral measure" which depends only on the composite geometry. In the previous sub-project the importance of horizontal fluid transport is described, and computation of these spectral measures provides a general technique for computing horizontal flow properties, as well as other parameters of interest.

Voter model and the fractal geometry of melt ponds (Rebecca Nickerson and Ken Golden): Interacting particle systems have been used to model the evolution of a broad range of systems. We have developed a simple voter-type model to study how melt ponds form. The key step is to mimic the assumption in the voter model that a voter may be more likely to vote for a candidate if his or her neighbors have. For melt ponds, a square is more likely to melt if more of its neighbors have melted.

Cheeger constants for melt ponds (Kasey Leavitt and Ken Golden): We have been developing methods of algorithmically mapping images of melt ponds onto random planar graphs. To measure key geometrical features of the ponds, we have been investigating how to compute so-called *Cheeger constants* for graphs representing melt pond configurations. This parameter is a measure of whether or not the graph has a "bottleneck," which is a critical geometrical feature controlling horizontal flow of melt water. The notion of the Cheeger constant should also be useful for analysis of the brine microstructure of sea ice.

Melt Ponds and Bifurcations in Climate Models (Ivan Sudakov and Ken Golden): As melt ponds grow and coalesce, their fractal dimension changes, which means that their areas don't grow as rapidly as their perimeters. Does this impact albedo and the dynamics of conceptual climate models? We are investigating this possibility.

Nonlinear PDE model for melt pond water depth (Court Strong and Ken Golden): In order to provide a physically based mathematical framework to complement our statistical physics analyses of melt pond fractal dimension, we have been working with a partial differential equation governing melt pond water depth h (Lüthje et al., 2006).

Numerical model for fluid flow through porous sea ice (Kyle Steffen, Yekaterina Epshteyn, and Ken Golden): Melt pond evolution is intimately related to how easy it is for fluid to flow or drain through the porous brine microstructure of the sea ice supporting the ponds. We have begun developing numerical models of this important process, and modifying existing random pipe models to investigate the effect of the presence of algal EPS on fluid permeability.

Field Project
Chris Polashenski and Ken Golden participated in the SUBICE (Study of Under ice Blooms In the Chuckchi Ecosystem) Expedition aboard the USCGC Healy for about six weeks during May and June of 2014 (Don Perovich was the leader of the ice team but was unable to travel due to a medical issue, Polashenski took over the leadership role). We looked at ice albedo and melt pond formation.

WORK COMPLETED

Image Acquisition. We are building a library of aerial and satellite imagery. So far we have compiled a few thousand aerial photographs of ponded sea ice plus approximately 50 satellite images.

Fractal dimension computation. In discovering that there is a transition in the fractal dimension of melt ponds, we needed to come up with a way of computing the fractal dimension from area-perimeter data on melt ponds. We developed a deterministic algorithm to do this. However, a statistical approach that creates a "best fit" fractal dimension curve for the given data set eluded us. Court Strong found such a method. It creates an optimal fit of a hyperbolic tangent model for the fractal dimension as a function of log A, where A is the area of the melt ponds. This algorithm now makes possible the fractal analysis of melt pond configurations produced by mathematical models, as well as raw melt pond data that we will be obtaining in the future.

Melt pond evolution models. The pond configurations in the continuum percolation model are for a surface produced by a Fourier series with random amplitudes and phases. These configurations look quite similar to actual melt ponds. Similarly, the voter model produces configurations that look like melt ponds, as does the Ising model. The challenge now is to better understand the basic physics of melt ponds and how the parameters of these models are related to melt pond characteristics. We have done this for an Ising model of melt pond evolution, having now incorporated ice-albedo feedback and the basic thermodynamics of melting ice.

Network model of horizontal fluid permeability. We have worked through examples where a complex melt ponds are mapped onto a resistor network. This network contains not only connectivity information about the different components of the pond**,** but the widths of narrow channels through which melt water must flow, for example, to be drained through a nearby seal hole. The permeability calculation depends on computing the effective conductivity of the network. We have implemented an exact formula for the conductivity of a random graph – based on an enumeration of trees of the graph via the determinants of adjacency matrices - in order to compute the horizontal fluid permeability. Moreover, we have developed an algorithmic approach to mapping melt pond images onto these networks.

Spectral Measures for Melt Pond Configurations. We have computed examples of spectral measures for discretizations of actual melt pond images, and have made significant advances in the underlying functional and numerical analysis needed for these computations.

Nonlinear PDE model for melt pond water depth. We developed code to numerically integrate the melt pond water depth PDE on grids with various horizontal resolutions, and initialized the model with topography adapted from LiDAR observations (e.g., Polashenski et al., 2010). This framework developed melt ponds with realistic fractal properties, and we are investigating how these properties depend on the specification of the initial topography.

Image analysis of melt ponds. Part of our effort is focused on exploring the evolution of melt pond fraction, number, size, and shape through the use of National Technical Means Imagery. This is a Lagrangian data set of imagery that tracks individual floes. An image processing technique has been developed to analyze melt pond formation and evolution during the summer melt season. Statistics can be extracted for an ensemble of ponds developing on an individual floe from the formation of discrete melt ponds to a network of connected melt features. From the processed imagery, pond area fraction, pond count, and average pond size can be calculated at several times throughout the season.

This method for image processing begins with an object based classification that includes a segmentation of the original image into features of similar spectral, spatial, and texture characteristics using the ENVI Feature Extraction workflow. A series of variables are extracted for each feature and construct a shapefile of polygons each with 21 attributes. A histogram analysis and stretch are performed to create additional attributes indicating pixel value relative to the entire image. A training set is then created from four different images varying in time of season and lighting conditions for classes: ice, open water, submerged ice, and ridges. A random forest classification is performed in Matlab to classify each segmented image using the training set. The result is a shapefile of classified polygons. The class called submerged ice is separated into ponds and submerged ice along floe edges using the spatial proximity to open water ARCGIS neighbor analysis.

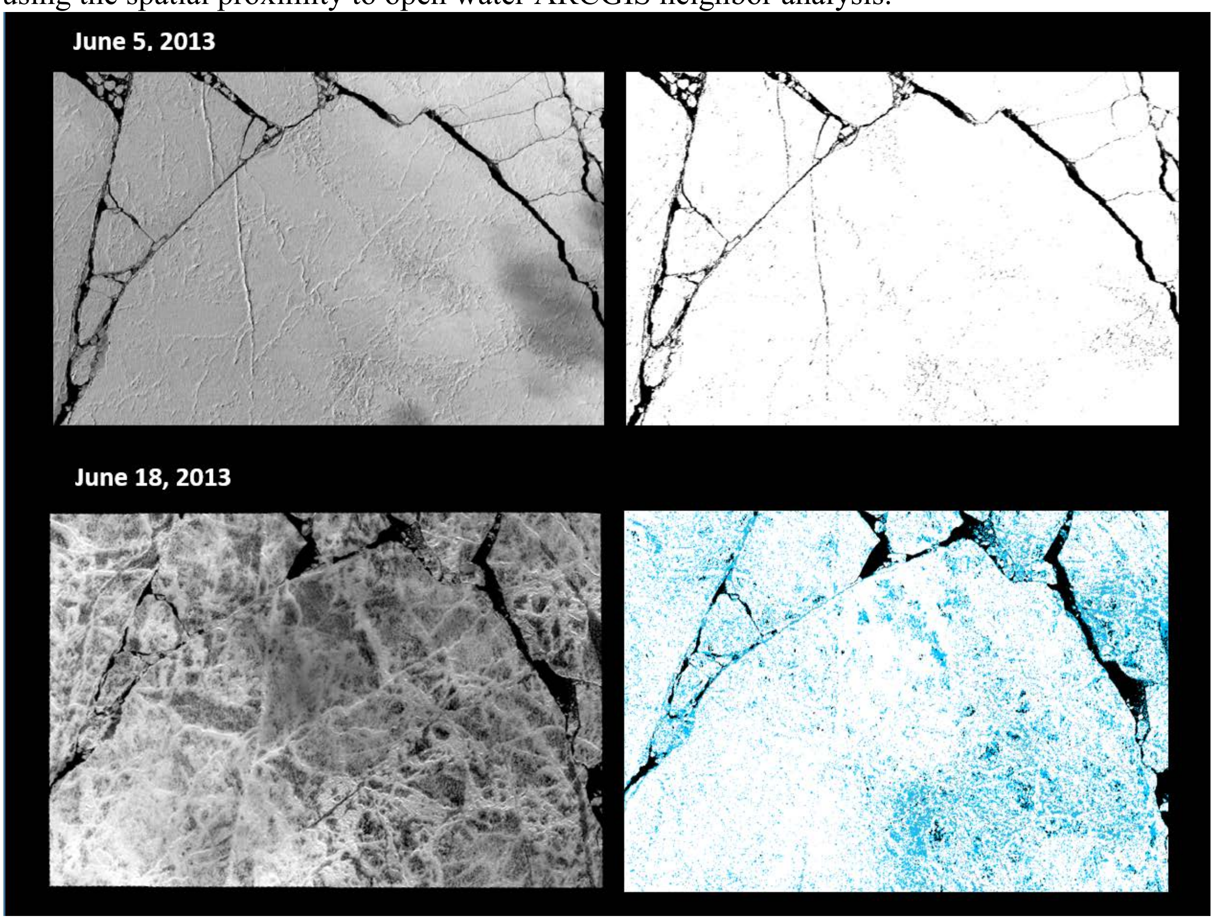

Figure 1. Images from June 5 and June 18, 2013. The left column shows the raw image and the right column the processed image.

RESULTS

Below we present abstracts from papers that contain results from some of the projects described above.

Arctic melt ponds and bifurcations in the climate system
I. Sudakov, S. A. Vakulenko and K. M. Golden

Abstract: Understanding how sea ice melts is critical to climate projections. In the Arctic, melt ponds that develop on the surface of sea ice floes during the late spring and summer largely determine their albedo - a key parameter in climate modeling. Here we explore the possibility of a conceptual sea ice climate model passing through a bifurcation point - an irreversible critical threshold as the system warms, by incorporating geometric information about melt pond evolution. This study is based on a bifurcation analysis of the energy balance climate model with ice-albedo feedback as the key mechanism driving the system to bifurcation points.

Ising model for melt ponds on Arctic sea ice
Y. Ma, I. Sudakov, and K. M. Golden

Abstract: The albedo of melting Arctic sea ice, a key parameter in climate modeling, is determined by pools of water on the ice surface. Recent observations show an onset of pond complexity at a critical area of about 100 square meters, attended by a transition in pond fractal dimension. To explain this behavior and provide a statistical physics approach to sea ice modeling, we introduce a two dimensional Ising model for pond evolution which incorporates ice-albedo feedback and the underlying thermodynamics. The binary magnetic spin variables in the Ising model correspond to the presence of melt water or ice on the sea ice surface. The model exhibits a second-order phase transition from isolated to clustered melt ponds, with the evolution of pond complexity consistent with the observations.

Network modeling of Arctic melt ponds
M. Barjatia, T. Tasdizen, B. Song, and K. M. Golden

Abstract: The recent precipitous losses of summer Arctic sea ice have outpaced the projections of most climate models. Efforts to improve these models have focused in part on a more accurate accounting of sea ice albedo or reflectance. In late spring and summer, the albedo of the ice pack is determined primarily by melt ponds that form on the sea ice surface. The transition of pond configurations from isolated structures to interconnected networks is critical in allowing the lateral flow of melt water toward drainage features such as large brine channels, fractures, and seal holes, which can significantly alter the albedo. Moreover, pond connectivity can also influence their effectiveness in breaking up an ice floe as the melt season progresses. Here we develop algorithmic techniques for mapping photographic images of melt ponds onto discrete conductance networks which represent the geometry of pond configurations and approximate the ease of lateral flow. We implement an image processing algorithm with mathematical morphology operations to produce a conductance

matrix representation of the melt ponds. Basic clustering and edge elimination using graph theory are then used to reduce the conductance matrix to include only direct connections. The results for images taken during different times of the year are visually inspected and the number of mislabels is used to evaluate performance.

Fractal properties of a continuum percolation model for the evolution of melt ponds on Arctic sea ice

B. Bowen, C. Strong, and K. M. Golden

Abstract: Melt ponds on Arctic sea ice are known to undergo a dramatic transition in fractal dimension as they grow and connect during the melt season. Here, we employ a continuum percolation model where the pond boundaries are the intersections of a horizontal plane with a random surface representing ice topography. We define a class of stochastic surfaces that replicate this fractal dimension shift, and we explore the fractal properties of the associated ponds as a function of their autocorrelation and anisotropy. We use two models to investigate the evolution of melt ponds - the level set percolation model where the melt ponds are the volume between the rising plane and the surface, and a partial differential equation model based on water mass conservation and accelerated melt rates due to ice-albedo feedback where water is present. Both models exhibit a transition in the fractal dimension, but we find that the partial differential equation model shifts to a larger fractal dimension. The water-enhanced melt rates deepen rather than widen the ponds, allowing them to grow and connect which increases perimeter without substantial expansion of their surface area.

Random matrix universality for connectedness transitions in composite materials

N. B. Murphy and K. M. Golden

Abstract: Random matrix universality in large complex systems, where the eigenvalues of random matrix models display universal statistical behavior, arises from a fine balance between chaos and order. Universality has turned up in so many seemingly unrelated problems that it can be thought of as a fundamental law, not unlike the central limit theorem. A generalization of classical universality has been successful in describing some chaotic quantum systems and disordered mesoscopic conductors which undergo transitional behavior as system parameters vary. We find that this generalized universality also governs transitional behavior in the effective transport properties of macroscopic composite materials. In particular, transport in composites displays critical behavior near transitions in the connectedness or percolation properties of a particular phase. The analytic continuation method provides rigorous integral representations for the bulk transport coefficients of such media. At the heart of the method is a family of random matrices, new to random matrix theory, which depend only on the composite geometry. Here we demonstrate that an onset of connectedness gives rise to striking transitional behavior in the long and short range correlations of the eigenvalues of the random matrices. Their statistics shift from weakly to highly correlated, or Poissonian toward Wigner-Dyson, as a function of system connectedness. This provides a mechanism for explaining the collapse of spectral gaps which control critical behavior of transport. The spectral transition is explored for random resistor networks, human bone, and some sea ice structures with a range of scales, whose effective properties are important in climate modeling.

Statement of significance: Since the 1950s during studies of atomic spectra, the striking phenomenon known as random matrix universality has emerged in the signal dynamics of the Internet, the departure times for bus systems, and even in the zeros of the famous Riemann zeta function. The eigenvalues or energy levels of random matrix models of such systems exhibit universal statistical behavior. A generalized universality has accurately described transitions in quantum and mesoscopic systems. We discover here that this generalized universality also describes transitions in the connectedness or percolation properties of composite materials with microstructural scales ranging from microns to kilometers. The associated transport properties of these composites arise in many engineering and technological applications, and play a key role in Earth's climate system.

Spectral measure computations for composite media

N. B. Murphy, C. Hohenegger, E. Cherkaev and K. M. Golden

Abstract: The analytic continuation method of homogenization theory provides Stieltjes integral representations for the effective parameters of composite media. These representations involve the spectral measures of self-adjoint random operators which depend only on the composite geometry. On finite bond lattices, these random operators are represented by random matrices and the spectral measures are given explicitly in terms of their eigenvalues and eigenvectors. Here we provide the mathematical foundation for rigorous computation of spectral measures for such composite media, and develop a numerically efficient projection method to enable such computations. This is accomplished by providing a novel formulation of the analytic continuation method which is equivalent to the original formulation and holds for both the finite lattice setting and the infinite settings. We also introduce a family of random bond lattices and directly compute the associated spectral measures and effective parameters. The computed spectral measures are in excellent agreement with known theoretical results. The behavior of the associated effective parameters is consistent with the symmetries and theoretical predictions of models, and the computed values fall within rigorous bounds. Some previous calculations of spectral measures have relied on finding the boundary values of the imaginary part of the effective parameter in the complex plane. Our method instead relies on direct computation of the eigenvalues and eigenvectors which enables, for example, statistical analysis of the spectral data.

Freshwater - the key to melt pond formation atop first year sea ice

C. Polashenski, K. M. Golden, E. Skyllingstad, and D. Perovich

Abstract: Melt pond formation atop Arctic sea ice is a primary control of shortwave energy balance and light availability for photosynthesis in the upper Arctic Ocean. The initial formation process of melt ponds on first year ice typically requires that melt water be retained on the surface of ice several to tens of centimeters above sea level for several days. Albedo feedbacks during this time period create below-sea-level depressions which remain ponds later in summer. Both theory and observations, however, show that sea ice is so highly porous and permeable prior to the formation of melt ponds that retention of water tens of cm above hydraulic equilibrium for multiple days should not be possible. Here we present results of percolation test experiments that identify the mechanism allowing above-sea level melt pond formation. The infiltration of fresh water into pore structure of the ice is responsible for plugging the pores with fresh ice, sealing the ice against further water percolation, and allowing water to pool above freeboard. Fresh meltwater availability and desalination processes, therefore, likely exert considerable influence over the formation of melt ponds. The findings demonstrate another

mechanism through which changes in snowfall on sea ice, already being observed, are likely to alter ice mass balance and highlight the importance of efforts to improve treatment of ice salinity in models.

Object-based detection of Arctic sea ice and melt ponds using high spatial resolution aerial photographs
X. Miao, H. Xieb, S. F. Ackley and D. K. Perovich

Abstract: High resolution aerial photographs used to detect and classify sea ice features, especially melt ponds, can provide extracted physical parameters to refine, validate, and improve climate models. However, manually delineating sea ice and melt ponds is time-consuming and labor-intensive. In this study, an object-based classification scheme is used to extract sea ice and melt ponds efficiently from 163 selected aerial photographs taken during the Chinese National Arctic Research Expedition (CHINARE 2010) to the western Arctic. The algorithm includes three major steps: (1) the image segmentation groups the neighboring pixels into objects according to the similarity of spectral and textural information; (2) the random forest ensemble classifier distinguishes four general classes: water, general submerged ice (GSI), shadow, and ice/snow; and (3) the polygon neighbor analysis further separates melt ponds and submerged ice from GSI according to their spatial relationships. The overall classification accuracy for the four general classes is 95.5% based on 178 ground reference objects. Furthermore, the producer's accuracy of 90.8% and user's accuracy of 91.8% is achieved for melt pond detection through 98 independent reference objects. For the 163 photos in the Arctic marginal ice zone examined, a total of 19,438 melt ponds larger than 1 m^2 are detected, with a pond density of 867.2 km-1. The average pond size is 32.6 m^2, and the average melt pond fraction is 5.63%. This method can be applied to massive high spatial resolution Arctic sea ice photographs for deriving detailed sea ice and melt pond distributions over wider regions, and extracting sea ice physical parameters and their corresponding changes between years.

IMPACT/APPLICATIONS

The simplicity of some of our melt pond models holds out the possibility of efficiently accounting for melt ponds and sea ice albedo in climate models. Our Ising model represents the first application of a sophisticated statistical physics model to studying the evolution of melt ponds. Our field work answers the fundamental puzzle about how melt ponds can form and persist atop highly permeable sea ice.

RELATED PROJECTS

NSF DMS Math Climate Research Network Grant (http://www.mathclimate.org/). This grant is partially funding our melt pond work and research on related sea ice properties.

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M. Lüthje, D. L. Feltham, P. D. Taylor & M. G. Worster (2006) Modeling the summertime evolution

of sea-ice melt ponds. *J. Geophys. Res.,* **111**, doi:10.1029/2004JC002818.

C. Polashenski, Z. Courville, D. K. Perovich, and D. Finnegan (2010) *Monitoring Melt Pond Evolution with LiDAR*, Presented at: International Glaciological Society Symposium on Sea Ice: May 31 - June 4, Tromso, Norway.

PUBLICATIONS

K. M. Golden, Mathematics of sea ice, invited article for *The Princeton Companion to Applied Mathematics*, N. J. Higham, M. Dennis, P. Glendinning, F. Santosa, and J. Tanner (Eds.), Princeton University Press [in press], 2014.

I. Sudakov, S. A. Vakulenko, and K. M. Golden, Arctic melt ponds and bifurcations in the climate system, Communications in Nonlinear Science and Numerical Simulation [in press, refereed], 2014.

N. B. Murphy, C. Hohenegger, E. Cherkaev and K. M. Golden, Spectral measure computations for composite media, *Communications in Mathematical Sciences*, 39 pp. [in press, refereed], 2014.

M. Barjatia, T. Tasdizen, B. Song, and K. M. Golden, Network modeling of Arctic melt ponds [submitted], 2014.

Y. Ma, I. Sudakov, and K. M. Golden, Ising model for melt ponds on Arctic sea ice [submitted], 2014.

N. B. Murphy and K. M. Golden, Random matrix universality for connectedness transitions in composite materials [submitted], 2014.

L. Istomina, G. Heygster, M. Huntemann, P. Schwarz, G. Birnbaum, C. Polashenski, D. Perovich, E. Zege, A. Malinka and A. Prikchach, The melt pond fraction and spectral sea ice albedo retrieval from MERIS data: validation and trends of sea ice albedo and melt pond fraction in the Arctic for years 2002-2011, *The Cryosphere* [submitted], 2014.

X. Ming, H. Xie, S. F. Ackley, D. K. Perovich, Object-based detection of Arctic sea ice and melt ponds using high spatial resolution aerial photographs, *Cold Reg. Sci. Tech.* [submitted], 2014.

HONORS/AWARDS/PRIZES

Kenneth M. Golden, University of Utah

2013 Guest of Honor, Institut des Hautes Etudes Scientifiques (IHES) Gala, Mathematics: Mind of the Earth, hosted by the French Ambassador to the US, Pierre Hotel, New York City

Selected invited lectures:

2013 Inaugural Bernoulli Society Public Lecture, 36th Conference on Stochastic Processes and their Applications, Boulder

2013 G. Milton Wing Lectures, University of Rochester, Rochester, NY

2013 Public Lecture, University of North Carolina, Chapel Hill

2013 Keynote Speaker, Mathematics of Planet Earth 2013, Platform for Mathematics in The Netherlands, Utrecht

2013 Invited Speaker, Fall Meeting of the American Geophysical Union (AGU), December 2013, Union Session on *Mathematics of Planet Earth*, San Francisco

2014 Science at Breakfast, College of Science, University of Utah, Salt Lake City

2014 Invited Speaker, Inaugural KOzWaves Conference (Kiwi-Aussie Waves), Newcastle, Australia

2014 Invited Address, Session on *Physics of Climate*, American Physical Society, Denver

2014 Math Encounters, Public Presentation Series (sponsored by the Simons Foundation), National Museum of Mathematics, New York City

2014 Public Lecture, 13th Continuum Models and Discrete Systems Symposium, Salt Lake City

2014 Lorentz Center Workshop on *Spatio-temporal dynamics in ecology*, Leiden, Netherlands

2014 Workshop on *Random matrix theory, algorithms & applications* at the Conference on Foundations of Computational Mathematics, Montevideo, Uruguay

2015 Invited Session on *Mathematics of Planet Earth* at the 2015 Joint Math Meetings, San Antonio

2015 Public Lecture, National Festival of Mathematics, Smithsonian Institution, Washington D.C.

Selected Media Coverage:

2013 Swiss Public Radio, *Trip to Alaska: On the trail of climate change*, T. Hausler, Three half-hour segments on our sea ice field work in the Arctic Ocean off Barrow, AK.

2014 NSF Science Nation (video): "Mathematician combines love for numbers and passion for sea ice to forecast melting."

2014 NBC News/NBC Learn video on *Science and Engineering of the 2014 Olympic Winter Games*, featured in “Science of Ice.”

Zeit Magazin, Wenn hier nichts mehr ist, ist es vorbei, T. Hausler, pp. 76-80, November 2013

livescience.com, Doing the math on polar sea ice melt, Tanya Lewis, March 2014.

ScientificAmerican.com, Mathematical patterns in sea ice reveal melt dynamics, Geoffrey Giller, March 2014. (Referred to as the *Indiana Jones of mathematics*.)